Hull Form Optimization for Early Stage Ship Design

Wesley Wilson, Dr. Dane Hendrix and Dr. Joseph Gorski
Naval Surface Warfare Center – Carderock Division
West Bethesda, MD

Abstract

Shape optimization is a growing field of interest in many areas of academic research, marine design, and manufacturing. As part of the CREATE Ships Hydromechanics Product, an effort is underway to develop a computational tool set and process framework that can aid the ship designer in making informed decisions regarding the influence of the planned hull shape on its hydrodynamic characteristics, even at the earliest stages where decisions can have significant cost implications. The major goal of this effort is to utilize the increasing experience gained in using these methods to assess shape optimization techniques and how they might impact design for current and future naval ships. Additionally, this effort is aimed at establishing an optimization framework within the bounds of a collaborative design environment that will result in improved performance and better understanding of preliminary ship designs at an early stage. The initial effort demonstrated here is aimed at ship resistance, and examples are shown for full ship and localized bow dome shaping related to the Joint High Speed Sealift (JHSS) hull concept.

Introduction

Any ship design inherently involves optimization, as competing requirements and design parameters force the design to evolve, and as designers strive to deliver the most effective and efficient platform possible within the constraints of time, budget, and performance requirements. A significant number of applications of computational fluid dynamics (CFD) tools to hydrodynamic optimization, mostly for reducing calm-water drag and wave patterns, demonstrate a growing interest in optimization. In addition, more recent ship design programs within the US Navy illustrate some fundamental changes in mission and performance requirements, and future ship designs may be radically different from current ships in the fleet. One difficulty with designing such new concepts is the lack of experience from which to draw from when performing design studies; thus, optimization techniques may be particularly useful.

These issues point to a need for greater fidelity, robustness, and ease of use in the tools used in early stage ship design. The Computational Research and Engineering Acquisition Tools and Environments (CREATE) program attempts to address this in its plan to develop and deploy sets of computational engineering design and analysis tools. It is expected that advances in computers will allow for highly accurate design and analyses studies that can be carried out throughout the design process. In order to evaluate candidate designs and explore the design space more thoroughly shape optimization is an important component of the CREATE Ships Hydromechanics Product. The current program development plan includes fast parameterized codes to bound the design space and more accurate Reynolds-Averaged Navier-Stokes (RANS) codes to better define the geometry and performance of the specified hull forms. The potential for hydrodynamic shape optimization has been demonstrated for a variety of different hull forms, including multi-hulls, in related efforts (see e.g., Wilson *et al*, 2009, Stern *et al*,

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14. ABSTRACT
Shape optimization is a growing field of interest in many areas of academic research, marine design, and manufacturing. As part of the CREATE Ships Hydromechanics Product, an effort is underway to develop a computational tool set and process framework that can aid the ship designer in making informed decisions regarding the influence of the planned hull shape on its hydrodynamic characteristics, even at the earliest stages where decisions can have significant cost implications. The major goal of this effort is to utilize the increasing experience gained in using these methods to assess shape optimization techniques and how they might impact design for current and future naval ships. Additionally, this effort is aimed at establishing an optimization framework within the bounds of a collaborative design environment that will result in improved performance and better understanding of preliminary ship designs at an early stage. The initial effort demonstrated here is aimed at ship resistance, and examples are shown for full ship and localized bow dome shaping related to the Joint High Speed Sealift (JHSS) hull concept.

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2007, Campana *et al*, 2006, Campana *et al*, 2009). The tools are basically in place for performing hydrodynamic shape optimization of a hull form, but a significant effort is needed to demonstrate this capability for hull forms currently of interest to the Navy, to include the capability in a useable package and process, and to validate the prediction capability.

The US Navy sees the need to change, at the highest levels, and to take greater advantage of expanding computational capability. This was recently addressed in a memorandum from COMNAVSEA, establishing high-level capability goals for NAVSEA design synthesis and analysis tools[1]. As part of Preliminary and Contract Design it was stated that: "The goal for synthesis and analysis tools used in this acquisition phase is enabling the completion of a design iteration in 8 to 10 weeks including insight as to changes needed for the next design iteration." RANS computations already have the capability to provide hydrodynamics predictions within this time frame. They are still too slow to provide a comprehensive analysis of all aspects of a Navy ship design, which are needed; however, they can be used for studies of resistance, powering, and maneuvering and by combining them with optimization techniques can provide the needed insight for design iterations.

The goal of the CREATE program is to is to impact design in a meaningful way with high fidelity hydrodynamic predictive tools. In order to do this it is necessary to get these codes into a design environment. This means automating the use of these codes as much as possible to allow for running many hull variants that can provide meaningful ship behavior information to a ship designer. Shape optimization is a key component of this effort, as well. Although the development of new software for future HPC resources is the plan for CREATE, there is also the near term CREATE goal of providing incremental capability and benefits throughout the CREATE program lifetime and part of that is using current software effectively. Consequently, a part of the CREATE Ship Hydromechanics Product is aimed at using existing codes for design studies of relevant hulls forms and combining them with shape optimization algorithms to achieve better performing concepts. This also sets the stage for the incorporation of the future CREATE high-end codes earlier into the design process as they become available. The higher-resolution physics-based RANS tools that are currently being used within the Navy are showing phenomenal capabilities for a wide range of geometries and conditions and address many of the hydrodynamic aspects of ship design. They are too slow for early stage design, but they do provide a modeling framework for developing the next generation of high resolution codes geared toward the next generation of computers, which can have an impact in the early stages of a design. Validation is also still an issue that must be addressed and will receive considerable attention throughout the effort. There have been numerous validation studies performed with these codes, but not in a framework that has yet engendered confidence in the codes for design. Consequently, the current effort is also geared toward systematic validation over a range of conditions for relevant hull forms. Ultimately, this will provide a design infrastructure to address many hull options.

Current efforts have focused on use of the hydrodynamic analysis tools that are currently implemented within the CREATE Integrated Hydrodynamic Design

[1] Memorandum from Admiral Sullivan on "Ship Design and Analysis Tools," dated 4 February, 2008.

Environment (IHDE) or are planned for implementation in the future. This includes both linear (using slender ship theory potential based methods) and non-linear (RANS) evaluations of hydrodynamic resistance and comparison with experimental data. In addition, efforts have focused on developing an optimization process that can be implemented within the IHDE framework. One of the key elements that is necessary for integration with a design environment is automation. To that end, an automated process has been implemented for determining the hull shape perturbations and evaluating the objective function for each perturbed shape for linear methods. As this process is expanded to include evaluations using RANS, automation will again be key, especially in relation to the grid generation process. This work is currently ongoing. With proper automation, it becomes possible to provide parametric information about changes to the global definition of the hull form that would help to guide much of the early stage design comparison studies and in the analysis of alternatives design stage. The optimization process could, for example, follow a set-based design approach by providing resistance information for a series of length and beam changes, or side hull clearance and stagger in the case of multi-hulls, which would still satisfy the overall design synthesis process.

With the ongoing development of this technology it is our hope and intent that the use of hydrodynamic evaluation and optimization tools within the CREATE IHDE design environment will aid current and future ship designers. The capability from this effort has the potential to significantly impact directly the issues that are of concern for current and future acquisition programs for US Navy ships.

Computational Tools

In this section follows some discussion of the computational tools being examined as part of this effort. In particular these tools are either currently implemented, or are slated for inclusion in the IHDE.

TSD (total ship drag) is a robust fast resistance prediction tool appropriate for early stage design developed by NSWCCD (Metcalf *et al.* 2004). The total drag of a ship as calculated by TSD is made up of the following components: wave-making resistance, frictional resistance, form resistance, transom drag, and other drag. Each resistance component is estimated in a way that is faithful to the physics of the problem. The wave-making resistance is computed using slender ship theory (Noblesse, 1983). The frictional resistance is estimated using the ITTC friction line. Form resistance is approximated from Series 58 data. Transom drag is divided into two components—a base drag component which is modeled based on empirical data from sub-sonic bullet tests, and a hydrostatic component which accounts for the missing hydrostatic pressure on a dry transom. Finally, an additional component of drag is modeled which accounts for other drag sources such as spray. This component is empirically based on Series 64 data and other forms with spray formation. All these components of drag respond to changes in the hull form and make TSD a tool that is appropriate for use with an optimization code.

TSD was used in two different modes for this study. These are determined by a user-specified parameter (kext), which sets the relative importance of speed vs. accuracy. In the fast mode (kext=-1), it computes Noblesse's zeroeth-order slender-ship approximation to the far field wave resistance where the source strength applied on a panel depends only on the x-component (flow direction) of the normal to the panel. In the slow mode

(kext=0), the zeroeth-order flow is computed at each panel on the hull. A local correction to the normal flow through the panel is then applied to the source strength at each panel before computing the wave resistance. This correction can be applied iteratively, but it is much more sensitive to panelization and is not guaranteed to converge.

CFDShip-Iowa is a general-purpose research, unsteady Reynolds-Averaged Navier-Stokes (URANS) CFD code developed at University of Iowa (UI) over the past ten years for support of student theses and research projects at UI, as well as transition to Navy laboratories, industry, and other universities. CFDShip-Iowa solves RANS equations using curvilinear overset grids. A combination of finite difference and finite volume methods are used to solve the equations. Second, third and fourth order upwind biased discretizations can be selected for the convection terms, and the second order central method is used for diffusion terms. The pressure-velocity coupling is achieved using either a projection algorithm (faster) or a PISO (Pressure Implicit with Splitting of Operators) method which is slower, though more robust. The resulting pressure matrix is solved with preconditioned Krylov-space type solvers using the PETSc package from Argonne National Laboratory. Boundary conditions are set using the graphical user interface in the GRIDGEN software from Pointwise, Inc. Implemented RANS turbulence closures include one-equation, two-equation, and an anisotropic explicit algebraic Reynolds stress model. A surface-capturing method using the level-set approach is used to model the free surface. In this method, a distance function is transported with the flow both in air and water, the interface being defined by the zero-contour (level set) of this function. This approach allows for the calculation of motions with large amplitudes, breaking waves and splashing.

One potential optimization framework that is currently being investigated is the SHAPE code, developed by SAIC (Kuhn *et al*, 2007). The SHAPE code determines changes to a baseline hull shape that produce improvements to some user-defined metric and are bounded by a set of local and generic constraints that are also prescribed by the user. The optimized hull shape is determined by examining how perturbations to the baseline hull shape change the evaluation of the objective function. The optimization routine is completely separate from the objective function evaluations. In this way, it is possible to utilize a variety of different analysis tools, including more computationally intensive tools, to perform the evaluations and build up a database that reflects the derivatives of the objective function for each of the perturbed hull shapes. The optimization routine itself, which employs linear programming, can then be done very quickly using the pre-generated database of derivatives. This also has the advantage of allowing the user to perform a variety of different design studies in a very short time; for example, changing the design constraints and assessing a new optimum design based on those constraints. Examples of this approach will be demonstrated for localized bow dome shape optimization studies.

One of the key elements necessary for integration with a design environment is automation. To that end, a semi-automated process has been implemented for determining the hull shape perturbations and evaluating the objective function for each perturbed shape using TSD. As this process is expanded to include evaluations using RANS, automation will again be key, especially in relation to the grid generation process. This work is currently ongoing.

Planned Implementation

The eventual goal of this effort is to be able to implement a hull form optimization strategy within the CREATE IHDE. The current plan is for this process to include a suite of different fidelity tools to arrive more efficiently at an optimum solution. The envisioned process would include using fast, robust potential flow solution methods to sweep the design space and create a response surface of the influence of geometry changes on the objective function (e.g., total resistance). To these results would be added a series of non-linear resistance evaluations, which could include predictions made by, for instance, a RANS tool. These newly added predictions would then be used to modify the response surface for use in the optimization procedure. It is the hope that this provides a process by which the designer can make an informed decision about the planned hull form. And using different fidelity tools provides a faster time to solution.

Validation Efforts

Current optimization efforts have focused on the Joint High Speed Sealift (JHSS) hull form, a very large (970ft) high-speed ship concept operating at a transit speed of at least 36 kts. This particular concept was chosen because it provides information related to a conventional propeller concept as compared with a waterjet propulsion concept, and also includes experimental data for four different bow variants. This provides for validation efforts and optimization efforts to be assessed for different propulsion configurations and for detailed feature shape optimization (e.g., bow shaping).

The work detailed in this paper focuses on the baseline shafts & struts (BSS) configuration for the JHSS hull concept. Denoted DTMB Model 5653, it was tested with four different bow shapes, including a stem bow and three different bow bulb profiles (Cusanelli, 2006). A photo of the model is given in Figure 1. The top view shows the entire model configured with the gooseneck bow, and with the rudders and propeller shafts and struts included. The lower left view shows three of the four bow shape variants (gooseneck bulb (GB), baseline bulb (BB), and elliptical bulb (EB) from left to right) and the lower right view again shows the gooseneck bulb in a closer view.

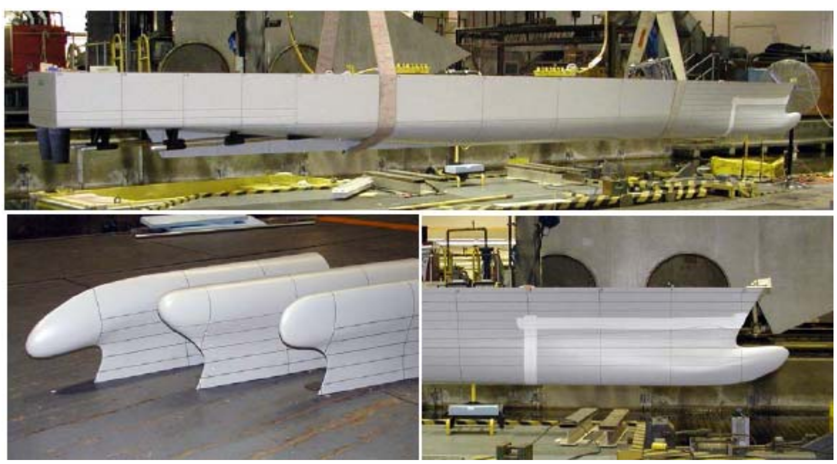

Figure 1. JHSS BSS Model 5653 (views of different bow sections).

In order to support the use of varying tool sets as part of this optimization framework, first validation studies have been performed using both CFDShip-Iowa and TSD. These were done for the JHSS Shafts & Struts (SS) Model 5653. Results for the predicted total

resistance coefficient are given in Figure 2 for the Baseline Bulb configuration. TSD was run in multiple modes to examine the effects.

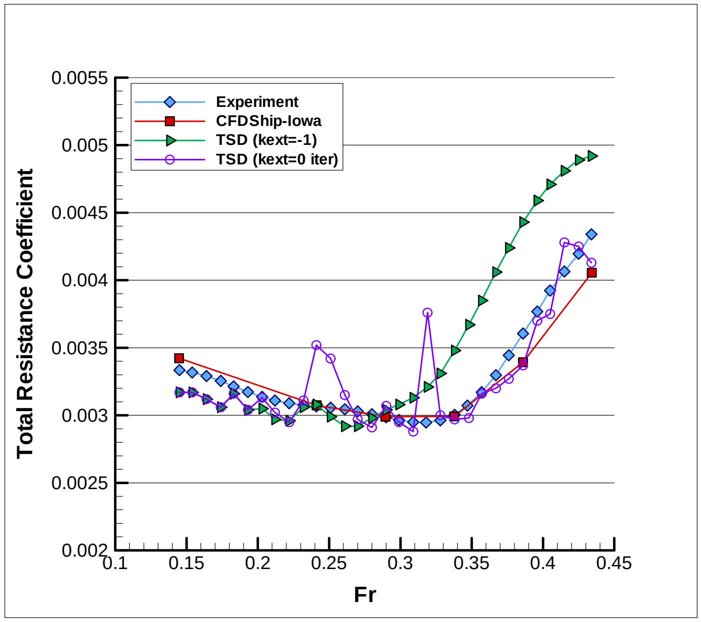

Figure 2. Total resistance coefficient vs. Froude number (Model 5653 Baseline Bulb).

The TSD results run using the fast mode indicate good agreement over the lower Froude number range but then deviate moderately for Froude numbers greater than about 0.3. But overall these results seem reasonable for fast, early stage design studies that examine gross changes. In addition, TSD does not incorporate changes to the model attitude due to dynamic sinkage and trim as it was executed in this case. TSD was also run using the slower, more accurate method. Here the corrected velocity field is iterated over to improve the accuracy. As shown in the figure, this produces a considerably more accurate result when compared with the experiments over the majority of the speed range. This is the mode that will be used to perform optimization studies shown later. There are some spurious results around Fr=0.25 and one point in particular at Fr=0.318. These are currently being investigated. The CFDShip-Iowa results also show good agreement and provide a further increase in accuracy due to a more realistic representation of the physics, as expected. Here the CFDShip-Iowa predictions are within 6.5% across the speed range, whereas the TSD predictions are within about 23% (fast mode) and 15% (slow mode, excepting the one spurious point at Fr=0.318, excepting the other spurious points this drops to 6.5%). The disparity, however, occurs with regard to the total time to solution, where CFDShip-Iowa required several hours as compared with only a few minutes for TSD using the slow mode and seconds for the fast mode for each speed. This is the primary driver for proposing a multi-fidelity solution strategy when dealing with resistance predictions and shape optimization for early stage design. In the interim, the current efforts used only TSD to evaluate the objective function. This provides for a quick solution time, and the validation exercise indicates sufficient accuracy in TSD to predict the trends as a function of speed. Also, since the optimization process examines the *change* in the total resistance, then as long as the tool is used consistently it is

believed that it can provide an improved design, but the *magnitude* of the predicted resistance will reflect the uncertainty of the prediction tool.

The previous example at model scale provides some confidence in the predictions; however, in general the influences of ship characteristics on ship scale performance are desired in the ship design process. Figure 3 shows a comparison of the predicted total resistance coefficient at ship scale. Here the 1957 ITTC friction line was assumed, and the TSD predictions were repeated for the appropriate Reynolds numbers to correspond to ship scale for the same geometry. By comparing Figure 3 with Figure 2 you can see the decrease in the total resistance coefficient by moving to the ship scale, as expected. Also, the trends in the TSD predictions, when compared with the model scale predictions, are very similar.

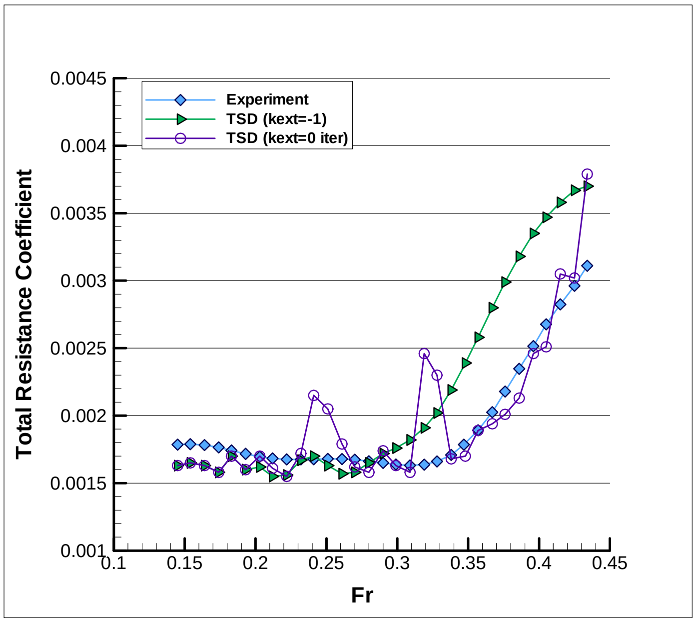

Figure 3. Total resistance coefficient vs Froude number (Model 5653 Baseline Bulb: Ship Scale).

Hull Form Optimization

In this section, the results of some of the preliminary optimization studies will be presented. The process for performing the optimization includes defining the baseline geometry, determining the objective function and design constraints, performing the assessment of the objective function for all of the basis pairs, and finally determining the hull shape that minimizes the objective function. For all of the examples given in the following sections, only the fast mode was used for the TSD predictions. This was done to try to gauge how effectively the fast, efficient method could be used for design optimization problems.

Full Ship Optimization for JHSS Concept Design

The optimization process was tested using the JHSS conventional Baseline Shaft & Strut (BSS) hullform concept. The physical model tests included variations in the model draft as well, to account for changes in the ship displacement (Light, Design, and Heavy). For the purposes of this effort, only the design displacement was considered. One case

that was examined was if the initial geometry consisted of the baseline bulb (BB) geometry that was tested. The objective function was the total resistance. An example optimization was performed for a single speed, corresponding to Froude number of 0.29, and in order to save computational time, the fast mode was used for the TSD evaluations. For this initial evaluation, the optimization was allowed to perturb the entire hull shape. The comparison of the baseline and optimized hull shape is shown in Figure 4.

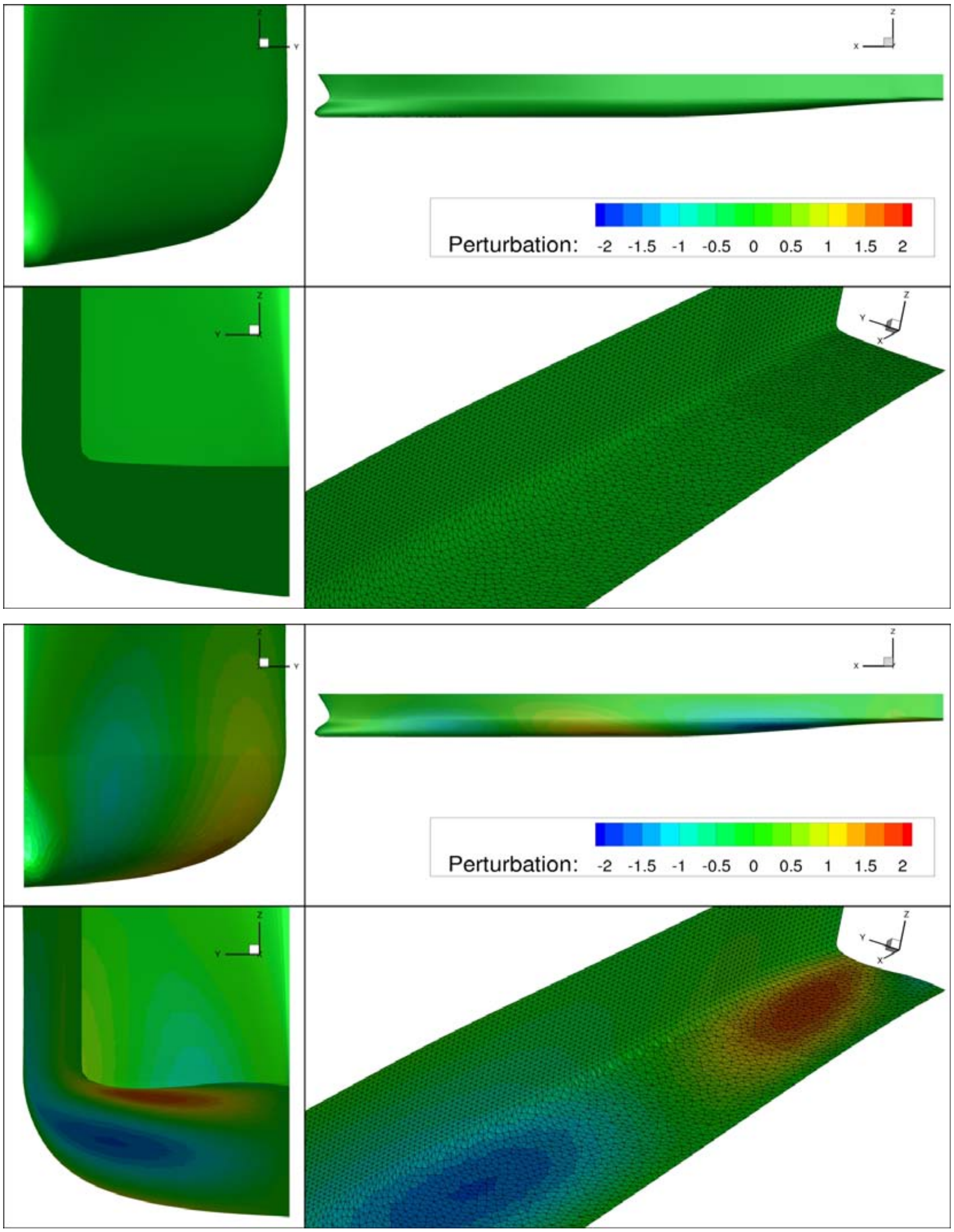

Figure 4. Comparison of Baseline and optimized geometry (Fr=0.29), perturbations in feet.

The design constraints that were used for this example were that the optimizer allowed no change in the total displacement of the ship and no change in the longitudinal center of

buoyancy. These were used just as constraints that might be typical of a design problem. The number of basis functions used was 7 in the longitudinal direction and 5 in the transverse direction, yielding a total of 35 degrees of freedom. In order to determine the predicted improvement in the optimized geometry, the final solution from the optimizer is then re-evaluated using the same solver used to evaluate the objective function. By comparing the optimized hull form with the baseline hull form, the total resistance was reduced by approximately 6.4%.

JHSS Bow Shape Optimization (Initial Geometry = Baseline Bulb)

In this case, the optimization procedure was limited to only focus on the bow section. The initial intent of performing this study was to compare an optimization process for determining the best bow shape to what was experimentally observed from the several bow variants that were tested with physical models. The single objective function optimization was performed for three separate speeds (20, 30, and 40 knots or 10.3, 15.5, and 20.6 m/s) corresponding to Froude numbers of 0.193, 0.290, and 0.386. This would provide an optimum for several speeds around the design speed of 36 knots.

The application of the basis pairs to determine the hull shape perturbations then was limited to the bow section. Also, no changes to the hull shape were permitted along the keel line up to the bulb. This was mostly a consideration for ease of fabrication. Figure 5 shows the region that was allowed to be modified. Additional design constraints included that there would be no change in the total displacement of the ship, and that there would be no change in the longitudinal center of buoyancy (LCB). Further constraints were added to provide smooth transitions in the hull shape definition from the unperturbed hull portion to the bow section. Finally the maximum perturbation was limited to 10.0 ft (3.048 m), which corresponds to approximately 1.0% of the LBP.

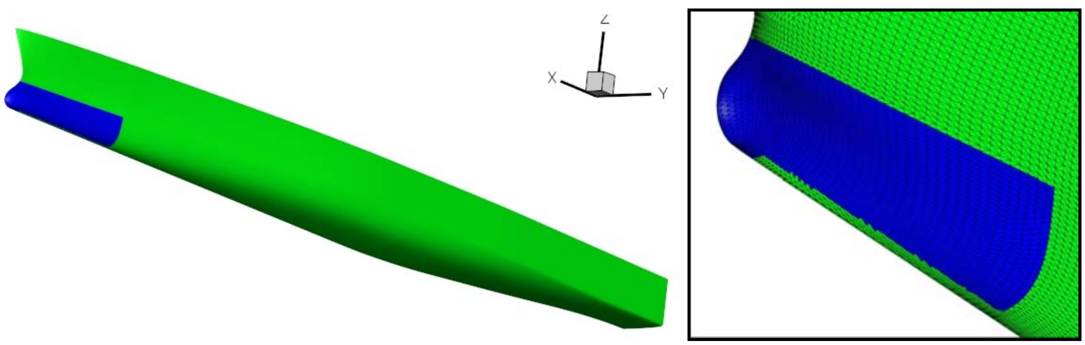

Figure 5. Design constraints applied to restrict hull shape perturbations to bow section.

The results of the single objective function optimization for Fr = 0.193 is given in Figure 6. Here the perturbation is given in ship-scale feet. The figure shows the hull form and computational mesh used in three views, from the bow looking aft, from the port side, and an isometric view. The graphic on the left shows the baseline hull form, which in this case was the original baseline bulb Model 5653 variant that was tested, but represented at ship scale. The graphic on the right shows the resulting hull shape after minimizing the total resistance at a forward speed of 20 knots, corresponding to Fr = 0.193. Due to the constraints applied to the optimization procedure, the only changes are

in the forward section of the bow and the bow bulb. As can be seen in the right graphic, the predicted optimum geometry includes some added volume to the forward end and top of the bow bulb, along with some small contraction of the lower bow section towards the keel and aft of the bulb. When re-evaluating the final result from the optimizer the total resistance was reduced by 3.5%. A similar comparison of the baseline and optimized hull shape for Fr = 0.290 is given in Figure 7. As shown in the graphic on the right, the optimization procedure at this speed attempts to alter the bow dome shape to include a lower protrusion. Because of the design constraint to maintain the total displacement, the optimizer also pulls in the hull shape moving aft from the bow bulb. In this case, the total resistance was reduced by approximately 2.0%.

Finally, the baseline and optimized hull shape for Fr = 0.386 is given in Figure 8. As shown in the graphic on the right, there is a continuation of the trend towards adding volume to the forward end and top portion of the bulb. In this case, when the optimized hull shape was re-evaluated using TSD in the fast mode, the total resistance increased just slightly by approximately +0.02%. What this means is that the improved hull shape determined by the optimizer turned out to not be an improved design when re-evaluated by the solver. This is why the re-evaluation step is so important when evaluating the designs that are generated. It is also likely that the constraint on the LCB is overly constraining the optimization process, as it is difficult to optimize a small bow region without allowing this to change.

At this point, some comments regarding the number of basis functions used is warranted. Recall that in the previous total ship optimization example, a total of 35 basis functions was used. In many cases this is found to be a sufficient number to examine the changes to the design. Generally speaking, one expects to find that the improvements to the baseline design should increase with increasing degrees of freedom, assuming the same constraints are used. In many cases, diminishing returns are observed from going to higher numbers of basis functions, due to decreasing impacts from shorter length scales. In the present bow shape optimization example, however, it was found that much better behavior was found by increasing the number of degrees of freedom. In this case, the number of basis functions used for Fr-=0.193 was 8 (longitudinal) and 6 (transverse) for a total of 48 degrees of freedom. The Fr = 0.29 optimization used 8x7 (total of 56) and the Fr = 0.386 optimization used 8x4 (total of 32).

Without additional testing of the resulting optimized shapes, we cannot make any definitive judgment as to the magnitude of the reduction in resistance. But all of this has proved to be a useful demonstration of this type of capability and the potential to incorporate shape optimization tools within the IHDE.

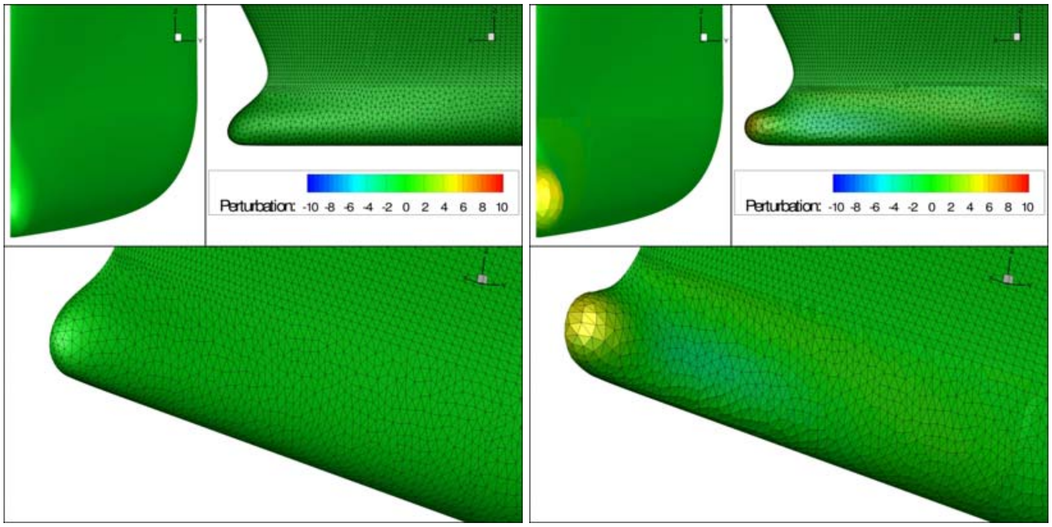

Figure 6. Comparison of baseline (BB) and optimized hull shape for Fr = 0.193.

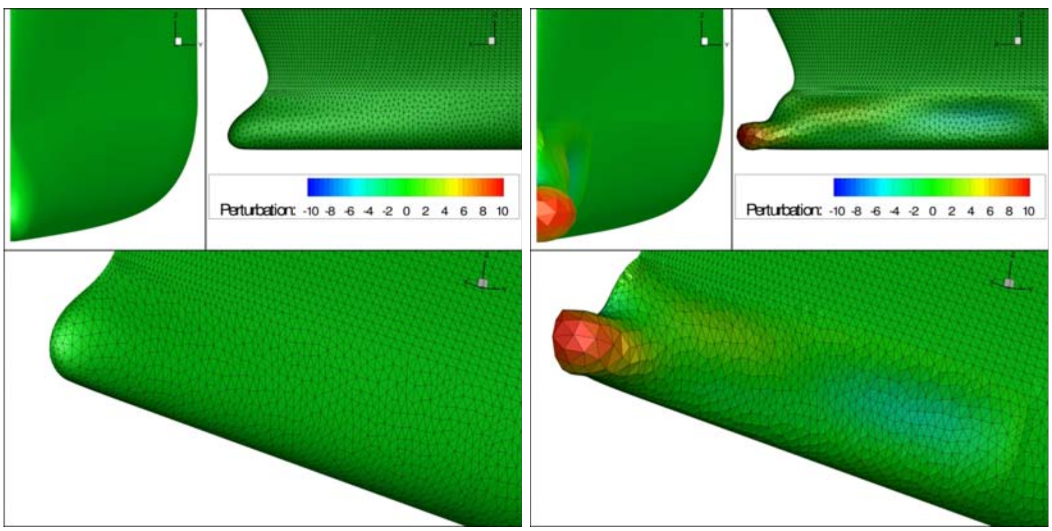

Figure 7. Comparison of baseline (BB) and optimized hull shape for Fr = 0.290.

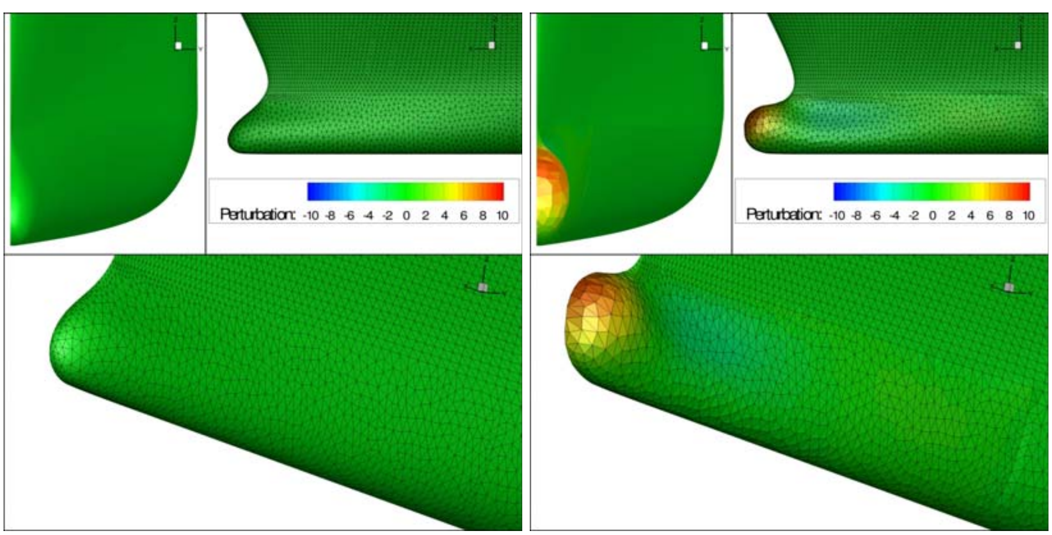

Figure 8. Comparison of baseline (BB) and optimized hull shape for Fr = 0.386.

Multi-Speed Optimization

Another caution in performing design optimizations for ships is that there can be significant dependence on the speed for which the design is optimized. In other words, a hull that is optimized for a single objective function at a given speed may perform much worse when at speeds other than the design speed. This is illustrated in Figure 9 which shows the predicted total resistance normalized by the total resistance of the baseline hull shape for each of the single speed optimized hull forms as a function of Froude number. In this example, the global constraints related to changes in the displacement and changes in the longitudinal center of buoyancy have been removed.

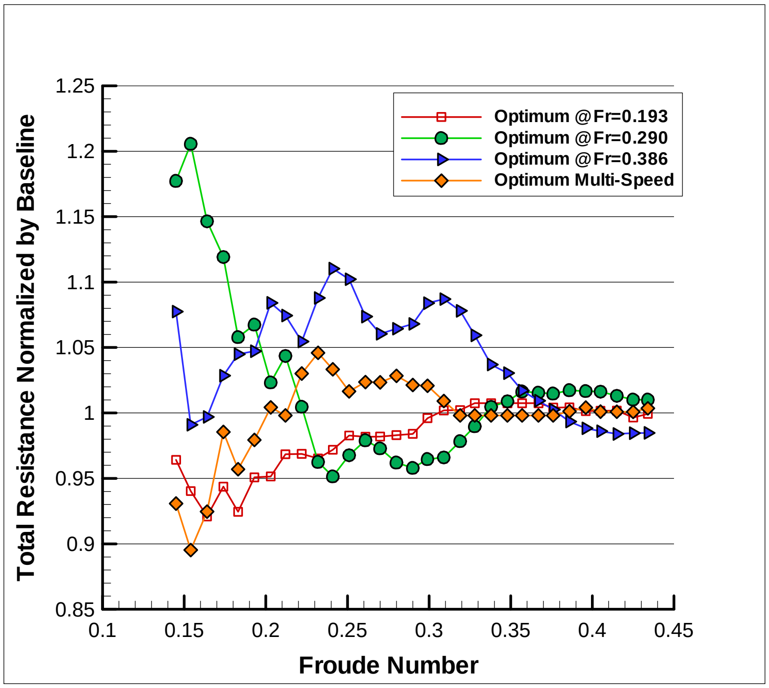

Figure 9. Total resistance normalized by baseline vs Froude number.

As shown in Figure 9, the performance of the hull shapes that are optimized based on a single speed, perform very well at the speed at which they were optimized. Moving away from those speeds, however, can cause a significant degradation in the performance. This is particularly true when examining the hulls optimized at Fr=0.29 and Fr=0.386 at the lower speed range (Fr < 0.2). Also shown in Figure 9 are the predicted normalized total resistance evaluations for a hull shape that was determined by using multiple speeds in evaluating the objective function. In this example, the three speeds were given weights of 0.5, 0.25, and 0.25 for the Fr=0.193, Fr=0.290, and Fr=0.386 conditions respectively. As indicated in the figure, this multi-speed optimized hull shape performs quite well across much of the speed range. In a real design application, it would be more appropriate to apply a weighting based on the ships intended speed or mission profile, but this serves as a simple example to demonstrate the capability for performing multi-speed optimization using the SHAPE framework.

Multi-Fidelity Optimization

As discussed, it is intended to implement the shape optimization process within the CREATE IHDE for early stage design studies. In order to provide improved accuracy, but still maintain efficient solutions, it is planned to incorporate a multi-fidelity approach to the solution of the objective function. This would involve response surface modeling for the potential flow methods, to be corrected through the use of non-linear resistance prediction tools. The current limitation is in regard to how to modify the volume mesh needed by the RANS code to predict the changes in the objective function for all of the hull shape perturbations that result from applying the basis function pairs. This work is ongoing.

Summary

This project is aimed at assessing the use of different hydrodynamic tools in hull shape optimization and in a larger ship design process. Current efforts have focused on validation, in order to provide confidence in the use of the tools, as well as automated processes that could be used within a ship design environment. Validation work has been performed for URANS and potential flow analysis codes that are planned for use in the CREATE IHDE. Here, attention to automation is key to providing ship designers with fast turnaround solutions and reasonably accurate predictions for early stage design.

A demonstration of a shape optimization framework has been performed using the JHSS hull concept as the hull form of interest. A preliminary study was performed using a fast low order solution method, and allowing the entire hull to be perturbed. In addition, two separate localized design studies were carried out, starting from a baseline bow configuration that was examined in a model test carried out at the Naval Surface Warfare Center – Carderock Division. The objective function was the total resistance, and design constraints were placed on the total displacement, and on the region of the ship hull that was allowed to change, in this case only the bow. The results of the shape optimization procedure demonstrated some improvements to the bow section that produced a reduction in total resistance of up to about 6%.

The eventual goal of this effort is to be able to implement a hull form optimization strategy within the CREATE IHDE. The current plan is for this process to include a suite of different fidelity tools to arrive more efficiently at an optimum solution. The envisioned process would include using fast, robust potential flow solution methods to sweep the design space and create a response surface of the influence of geometry changes on the objective function (e.g., total resistance). To these results would be added a series of non-linear resistance evaluations, which would be used to modify the response surface for use in the optimization procedure. It is the hope that this will provide a balance between solution accuracy and time to solution that will be attractive to the ship design community. Work related to implementing the necessary tools for performing non-linear resistance evaluations within the optimization framework is ongoing.

With the ongoing development of this technology it is our hope and intent that the use of hydrodynamic evaluation and optimization tools within the CREATE IHDE design environment will aid current and future ship designers. The capability from this effort has the potential to significantly impact directly the issues that are of concern for current and future acquisition programs for US Navy ships.

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